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Decay modes and lifetime of negative heavy mesons

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With 2 figures in the text

ABSTRACT

21 events representing possible decays of a negative K-meson in emulsion have been measured in order to get the relative abundances of different decay modes, an estimate of the contamination from nuclear reactions and a determination of the mean lifetime. Events consistent with τ^-, $K_{\mu 2}^-$, $K_{\mu 3}^-$, $K_{\pi 2}^-$, $K'^-_{\pi 3}$ and $K_{\beta 3}^-$ were found. The ratio $\tau^-/K_L^- + \tau^- = 3/20 = 0.15$ and $K_{\pi 2}^-/K_{\mu 2}^- = 3/7 = 0.43$. The percentage of nuclear reactions among the events with one charged secondary was ~ 20 %. The mean lifetime $\tau_{K^-} = (1.50^{+0.45}_{-0.30}) \times 10^{-8}$ sec. Three τ^- are reported and from one τ^- the mass of the negative τ-meson was $m_{\tau^-} = 494.4 \pm 1.2$ MeV.

1. Introduction

The relative frequences of different decay modes and lifetimes of machine produced positive, heavy mesons have been extensively studied in the last years by means of emulsion technique [1, 2] and counters [3]. The same problem for negative heavy mesons is comparatively much more difficult due to the strong nuclear interaction of the negative mesons. The lifetime has also been determined by means of emulsions [4–10] and counters [11] and some data on decay modes have appeared [7, 8, 12]. The only possible approach as regards decay modes and relative abundances so far seems to be identification of individual decays in flight in emulsions, cloud chambers or bubble chambers. The lifetime and decay mode determinations are subject to possible systematic errors due to the difficulty of distinguishing between a one charged pion mode of decay and a nuclear reaction giving rise to one pion. In the present paper 18 possible decays into one charged secondary out of a sample of 20 have been measured (Part 2, 3) in order to classify the event as a decay or nuclear reaction (Part 4). In Part 5 we discuss the relative frequences. Measurements on three τ^- are reported in Part 6 and an estimate of the mean lifetime of the K^- is given in Part 7.

2. Details of interactions in flight

The experiment was carried out in two Ilford G 5 emulsion stacks exposed at the Bevatron. 41 m of K^- meson track length have been followed in an unbiased way by "along the track scanning", 10 m in the energy interval 0–140 MeV (stack 1) and 31 m in the interval 0–90 MeV (stack 2). Experimental details will be published elsewhere [13]. 208 interactions in flight were found with the following characteristics.

A. Events with at least 1 black prong $\geqslant 5\ \mu m$	159
B. Events with 1 min. prong or pion and blob $< 5\ \mu m$ or clear electron	4
C. Events with 1 min. prong or light meson only	20
D. Zero prong stars with blob $< 5\ \mu m$ or clear electron	3
E. Zero prong stars with clean end	19
F. τ^-	3

A clear blob or Auger electron has been taken as an indication of a nuclear reaction. All events of type C except two (events no. 10 and 18, next section) have clean interaction points. The two ambiguous cases have been included due to the strict requirement of clear blobs or electrons. Decays into one charged particle are represented by events of type C and type E, if the secondary is not seen. The minimum grain density was 170/mm (400 MeV/c pions) in the high energy stack and 200/mm (300 MeV/c pions) in the low energy stack.

3. Measurements on the possible decays in flight

The events with one minimum ionising prong or pion were divided into two groups according to dip angle. In the first group consisting of secondaries with a dip angle less than 15° in unprocessed emulsion all secondaries were followed until they interacted or left the stack. In no case was it possible to stop the secondary. Scattering measurements were performed over the entire length of the track in most cases. The basic cell length was $t = 100\ \mu m$ and noise was eliminated between $t - 2t$ and $t - 3t$ and the weighted mean used. The scattering constant was taken from Voyvodic [14]. The influence of distortion was investigated by calculating the third differences and for the flat tracks in question it was found to be negligible. The ionisation of the track was determined by counting at least 1000 grains. Where possible a discrimination between π and μ was made. All scattering measurements were performed with a Koristka MS 2 microscope.

Table 1. Events with one charged secondary and dip angle $< 15°$.

Event no.	Primary kinetic energy MeV	Secondary track				Remarks
		Space angle, degrees[a]	Dip angle, degrees[b,c]	Followed mm	$p\beta$ MeV/c	
1	35 ± 2	46.9	-8.6	77.5	279 ± 20	
2	93 ± 7	19.2	$+9.6$	106.2	402 ± 21	
3	79 ± 4	26.0	0	23.0	378 ± 25	
4	22 ± 2	59.2	$+11.7$	15.8	244 ± 18	
5	30 ± 1	63.5	$+12.4$	9.3	233 ± 25	
6	75 ± 4	19.9	$+13.1$	28.1	241 ± 16	
7	113 ± 7	27.1	-5.4	12.1	337 ± 32	
8	68 ± 4	40.5	0	87.7	147 ± 3	Identified π
9	38 ± 3	79.3	-7.4	42.8	69 ± 6	Identified electron
10[d]	48 ± 4	43.8	-8.8	38.3	162 ± 10	Identified π
11	48 ± 4	28.0	-8.3	94.9	239 ± 12	Identified π

[a] With respect to the primary.

[b] In unprocessed emulsion.

[c] + to surface, − to glass.

[d] Possible electron at the decay point.

Table 2. Events with one charged secondary and dip angle $>15°$.

Event no.	Primary kinetic energy MeV	Secondary track			Remarks
		Space angle, degrees[a]	Dip angle, degrees[b, c]	$p\beta$ from g^* MeV/c	
12	62 ± 4	137.5	-39.8	$\pi\ 170 \pm 16$ $\mu\ 128 \pm 12$	
13	62 ± 4	51.5	$+22.9$	$\pi > 250$ $\mu > 185$	
14	39 ± 4	42.0	$+24.3$	$\pi\ 190 \pm 20$ $\mu\ 142 \pm 15$	
15	67 ± 4	148.5	-30.3	$\pi\ 49 \pm 1^d$	π^- stopped
16	34 ± 4	133.0	-21.6	$\pi\ 112 \pm 8$ $\mu\ 83 \pm 6$	
17	49 ± 4	142.0	$+19.1$	$\pi\ 83 \pm 6$ $\mu\ 63 \pm 4$	
18[e]	66 ± 4	22.4	-17.6	$\pi\ 145 \pm 10$ $\mu\ 108 \pm 5$	
19	103 ± 9	—	$+90$	—	
20	69 ± 4		-85	—	

[a] With respect to the primary.
[b] In unprocessed emulsion.
[c] + to surface, − to glass.
[d] From range.
[e] Possible blob at the decay point.

The energy of the primary K-meson was obtained by taking the weighted mean of the estimates from $p\beta$, g^*–residual range and the known residual range in the stack.

In this way 11 of the 20 events of type C were measured. In Table I we give details of the events and the results of the scattering measurements.

In the second group with secondaries of a dip angle more than 15° in unprocessed emulsion an estimate of $p\beta$ was made from g^*. A precise knowledge of the g^*–$p\beta$ relation was necessary and two points were very accurately determined, one at 148 MeV/c pions from $\Sigma^+ \to \pi$ at rest and one at 300 MeV/c pions in the beam. In the last case interacting π's were chosen as this was found to give much more consistent results than random selection of apparent minimum tracks. The shape of the g^*–$p\beta$ curve between 148 to 300 MeV/c was taken from the work of Alexander and Johnston [15]. For $p\beta < 148$ MeV/c the calibration was obtained from stopping π-mesons in the stacks. Each plate was normalised by counting at least 1000 grains. The ionisation of each track was measured by counting $\geqslant 1000$ grains in $\geqslant 3$ different plates.

Details of this group of events are given in Table 2. As the secondary is not identified we get two estimates of $p\beta$ by assuming either a π-meson or a μ-meson. For the last two events the secondary was too steep to be measured.

4. Interpretation in terms of decay modes

For each event we made a graphical construction [16, 17] of the relativistic decay kinematics and obtained the expected $p\beta$ for the different possible decay modes

$K_{\mu 2} \rightarrow \mu + \nu$ $p^*_\mu =$ 236 MeV/c (In C.M .S.)
$K_{\pi 2} \rightarrow \pi + \pi^0$ $p^*_\pi =$ 205 MeV/c
$K_{\mu 3} \rightarrow \mu + \nu + \pi^0$ $(p^*_\mu)_{\max} =$ 215 MeV/c
$K'_{\pi 3} \rightarrow \pi + \pi^0 + \pi^0$ $(p^*_\pi)_{\max} =$ 133 MeV/c
$K_{\beta 3} \rightarrow e + \nu + \pi^0$ $(p^*_e)_{\max} =$ 228 MeV/c

We give a summary of the results in Table 3 together with a tentative assignment of decay mode, where possible, for each event. Only the relevant expected $p\beta$ are quoted, the other modes of decay are ruled out. An event is defined as consistent with a decay mode, if the measured $p\beta$ and g^* lie within two standard deviations from the expected $p\beta$ and g^*. For the first group of events (1–11) the interpretation, within the limits of error, is fairly unique except in one case (event no. 7). If the measured $p\beta$ is consistent with $p\beta$ from a two-body mode of decay ($K_{\mu 2}, K_{\pi 2}$) as well as from a three-body mode of decay ($K_{\mu 3}$) we prefer the interpretation of the event as $K_{\mu 2}$ or $K_{\pi 2}$. If the relative frequences of the negative $K_{\mu 2}(K_{\pi 2})$ and $K_{\mu 3}$ are of the same order as the positive ones, 59 % (27 %) and ~3 % respectively [18], this will introduce only a small error. The fact that one would expect only a small number of $K_{\mu 3}$ with a high energy muon further strengthens this argument. If, on the other hand, the relative frequency of $K^-_{\mu 3}$ will not be much less than that of $K^-_{\mu 2}(K^-_{\pi 2})$ the error will be serious. It is assumed, however, that this is not the case.

The $K_{\beta 3}$ mode of decay can in most cases be ruled out on the basis of the measured g^*. For the events nos. 4, 5, and 6 the $K_{\beta 3}$ decay mode is also consistent according to our definition although g^* indicates a μ-meson rather than an electron of plateau ionisation. The agreement with the expected unique $p\beta$ from the $K_{\mu 2}$ has been taken as argument against $K_{\beta 3}$ in the first two cases and g^* is rather strong evidence for a μ-meson in the last case.

In the following the events are discussed in more detail.

Events 1–5. These events are unambiguous decays in flight. It is very unlikely that a nuclear interaction in flight will give rise to a π-meson of the $p\beta$ indicated. While a single event cannot be taken as a proof for the $K^-_{\mu 2}$, as can be seen from the standard errors involved, we think the group as a whole is good evidence for the existence of the $K^-_{\mu 2}$ mode of decay. In Fig. 1 we give the distribution of the momentum p^* in the K^- frame of reference assuming the secondary to be a μ-meson. The distribution is consistent with a unique value of $p^*_\mu = 236$ MeV/c. The spread in the distribution is smaller than would be expected from the standard deviation on each measurement. In view of the small numbers involved, we regard this as a pure statistical fluctuation.

Event 6. Although the μ cannot be identified with certainty the g^* value of 1.00 ± 0.04 supports the interpretation of the secondary as a μ-meson. The corresponding g^* for a π-meson or an electron would be 1.06.

Event 7. It is impossible to distinguish between a π and a μ in the $p\beta$-region concerned. The identification is only tentative and rests on the arguments given above.

Event 8. Details of this event have already been published [19]. $T^*_{\pi^-} = 47 \pm 2$ MeV in the C.M.S.[1] The absence of blob or electron has been taken as evidence for a decay. A nuclear reaction is also possible.

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[1] The momentum of the primary was incorrectly stated as 203 ± 7 MeV/c in ref. [19]. The correct value is 268 ± 8 MeV/c, which changes the value of T_{π^-} to 47 MeV.

Table 3. Measured $p\beta$ and expected $p\beta$ for different decay modes.

Event no.	$p\beta$ MeV/c measured	$p\beta$ MeV/c expected	Consistent with	Preferred interpretation
1	279 ± 20	$K_{\mu2}$ 279 $K_{\mu3} \leqslant 250$ $K_{\pi2}$ 235	$K_{\mu2}$, $K_{\mu3}$	$K_{\mu2}$
2	402 ± 21	$K_{\mu2}$ 403 $K_{\mu3} \leqslant 367$ $K_{\pi2}$ 355	$K_{\mu2}$, $K_{\mu3}$	$K_{\mu2}$
3	378 ± 25	$K_{\mu2}$ 370 $K_{\mu3} \leqslant 333$ $K_{\pi2}$ 317	$K_{\mu2}$, $K_{\mu3}$	$K_{\mu2}$
4	244 ± 18	$K_{\mu2}$ 241 $K_{\mu3} \leqslant 217$ $K_{\pi2}$ 200	$K_{\mu2}$, $K_{\mu3}$, $K_{\beta3}$	$K_{\mu2}$
5	233 ± 25	$K_{\mu2}$ 231 $K_{\mu3} \leqslant 214$ $K_{\pi2}$ 193	$K_{\mu2}$, $K_{\mu3}$, $K_{\beta3}$	$K_{\mu2}$
6	241 ± 16	$K_{\mu3} \leqslant 341$ $K_{\pi2}$ 327 $K'_{\pi3} \leqslant 215$	$K_{\mu3}$, $K_{\beta3}$	$K_{\mu3}$
7	337 ± 32	$K_{\mu2}$ 450 $K_{\mu3} \leqslant 355$ $K_{\pi2}$ 340	$K_{\mu3}$, $K_{\pi2}$	$K_{\pi2}$
8	147 ± 3	$K'_{\pi3} \leqslant 185$	$K'_{\pi3}$	$K'_{\pi3}$
9	69 ± 6	$K_{\beta3} \leqslant 226$	$K_{\beta3}$	$K_{\beta3}$
10	162 ± 10	$K_{\pi2}$ 244 $K'_{\pi3} \leqslant 143$	None	Nuclear reaction
11	239 ± 12	$K_{\pi2}$ 279 $K'_{\pi3} \leqslant 173$	None	Nuclear reaction
12	π 170 ± 16 μ 128 ± 12	$K_{\mu2}$ 117 $K_{\mu3} \leqslant 103$ $K_{\pi2}$ 74	$K_{\mu2}$	$K_{\mu2}$
13	$\pi > 250$ $\mu > 185$	$K_{\mu2}$ 275 $K_{\mu3} \leqslant 246$ $K_{\pi2}$ 230	$K_{\mu2}$, $K_{\mu3}$	$K_{\mu2}$
14	π 190 ± 20 μ 142 ± 15	$K_{\mu3} \leqslant 257$ $K_{\pi2}$ 243 $K'_{\pi3} \leqslant 144$	$K_{\mu3}$	$K_{\mu3}$
15	π 49 ± 1	$K_{\pi2}$ 63 $K'_{\pi3} \leqslant 17$	None	Nuclear reaction
16	π 112 ± 8 μ 83 ± 6	$K_{\mu2}$ 143 $K_{\mu3} \leqslant 126$ $K_{\pi2}$ 101	$K_{\mu3}$, $K_{\pi2}$	$K_{\pi2}$
17	π 83 ± 6 μ 63 ± 4	$K_{\mu2}$ 124 $K_{\mu3} \leqslant 108$ $K_{\pi2}$ 81	$K_{\mu3}$, $K_{\pi2}$	$K_{\pi2}$
18	π 145 ± 10 μ 108 ± 5	$K_{\mu3} \leqslant 329$ $K_{\pi2}$ 310 $K'_{\pi3} \leqslant 197$	$K_{\mu3}$, $K'_{\pi3}$	See discussion

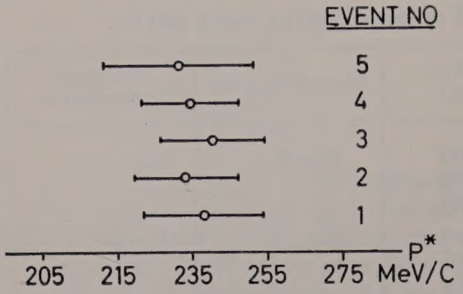

Fig. 1. Distribution of the momentum p^* of the secondary μ-meson in the K^- frame of reference for the events 1–5 consistent with the $K_{\mu 2}$ mode of decay.

Event 9. The identification of the electron is certain and the event is conclusive evidence for the $K_{\beta 3}^-$ mode of decay.

Events 10–11. These events are not consistent with any decay mode. They are interpreted as interactions in flight giving rise to one charged pion only.

For the second group of events the identification is less certain. With regard to the value of $p\beta$ all the events can arise from a nuclear reaction. If, however, most of the events are decays, the identification is significant. It has been suggested [20] that there is a high probability of obtaining by chance the kinematics of $K_{\pi 2}^-$. This question cannot be settled by the present experiments. We assume that the events leading up to the $K_{\pi 2}^-$ kinematics are decays in flight. The number of the $K_{\pi 2}^-$ mode of decay may therefore be regarded as an upper limit.

Events 12–13. In the last case we could only obtain a lower limit on $p\beta$ as the g^* $-p\beta$ relation flattens out towards high $p\beta$. The lower limit was deduced from $g^* = 0.97 +$ two times the standard deviation $= 1.05$. The $K_{\mu 2}^-$ interpretation is to be preferred as g^* indicates a $(p\beta)_\mu \sim 250$–300 MeV/c and this would mean a high energy μ from $K_{\mu 3}^-$. The decision is rather uncertain.

Event 15. The π^- was stopped in the stack. The range was 12.66 mm. Unfortunately it suffered a 96° scattering after 0.78 mm. In order to fit the kinematics of $K_{\pi 2}^-$ it must have lost 7 MeV in the collision. The ratio of g^* before and after the collision is 1.00 ± 0.05. A change of 7 MeV in energy would require a change in g^* of 20 %. We are forced to conclude that the event is a nuclear interaction.

Event 18 had a probable blob at the decay point. In the following analysis it is counted as a nuclear reaction in order not to underestimate the contamination from interactions.

5. Discussion of the relative abundances

In the last section we obtained out of 18 events, $7K_{\mu 2}^-$, $2\ K_{\mu 3}^-$, $3\ K_{\pi 2}^-$, $1\ K_{\pi 3}'^-$, $1\ K_{\beta 3}^-$ and 4 nuclear reactions. Thus the percentage of nuclear interactions among events with one charged thin prong is ~ 20 %. This is an overestimate as we have counted event 18 as a reaction. We think it is justified in view of the fact that the rare modes of decay are too numerous in comparison with what one would expect if the ratios were the same as for K^+. This might indicate that a systematic error still remains or that the relative abundances are not the same for K^- and K^+.

The number of the probably rare decay modes $K_{\mu 3}$ and $K_{\pi 3}'$ is not likely, however,

Table 4. The relative frequency of τ^-.

No. of τ^-	No. of K_L^-	$\tau^-/K_L^-+\tau^-$	References
2	42^a	5%	[7]
3	36^a	8%	[10]
3	17	15%	Present experiment

[a] Not corrected for nuclear interactions.

to have been overestimated. One can compare the number of interactions at rest and in flight with one pion only and clean interaction point. In our case this type of reaction occurs in 9 out of 818 interactions at rest. If it occurs with the same frequency in flight one would expect ~2 events, whereas we have estimated 4. The number of $K_{\mu 3}^-$ and $K_{\pi 3}'^-$ should thus reflect a real trend in the relative abundances of the negative heavy mesons.

In order to get the total number of decays in flight we need an estimate of the number where the secondary is not seen. The 19 zero prong stars consist of K^- + free proton charge exchange scattering, nuclear interactions and decays in flight. An indication that the latter fraction is not large is that the zero prong events are evenly distributed in depth in the emulsions. They have also been carefully examined by different observers. We have deduced an upper limit for the fraction of lost π-mesons from K^--stars at rest with one minimum prong. If θ is the angle between the π-meson and the normal to the emulsion plane we assume the plotted distribution in $\cos\theta$ to be isotropic and that all flat π-mesons are found. The fraction of lost π-mesons was 16 % in our case. The true percentage in case of decays in flight will lie between 0–16 %. We take 5 % as a probable figure. This increases the events of type C from 20 to 21. Subtracting 20 % interactions we are left with a total number of decays equal to $17K_L^- + 3\tau^-$.

The relative frequency of τ^- together with results from other experiments is given in table 4.

The combined result for the ratio $\tau^-/K_L^- + \tau^-$ is 8.4 ± 3.0 %. If we correct the number of K_L mesons in the other experiments by 20 % for nuclear reactions we arrive at a ratio of 10.0 ± 3.6 %. The corresponding ratio for $\tau^+/K_L^+ + \tau^+$ is 6.1 ± 0.3 % [19]. The difference is not yet significant and the ratio may well be the same for K^- and K^+. One can further conclude from the analysis given in the last section that $K_{\mu 2}^-$ is the predominante mode of decay for the negative K-meson. Our estimate for the $K_{\pi_2}^-/K_{\mu 2}^-$ ratio is $3/7 = 0.43$. This is an upper limit as has been previously pointed out. Within the meagre statistics available this is in agreement with the corresponding positive ratio $K_{\pi 2}^+/K_{\mu 2}^+ = 0.46$.

For the rest of the decay modes the numbers are too small to permit any conclusions.

6. Measurements on the τ^-

Three events were compatible with a τ^- decay. In event 21 one π^+ decayed at rest, one π^- gave a star at rest and the third pion interacted in flight. This event occurred in stack 1, where the density and the thickness of each emulsion sheet had been measured at the time of exposure. We therefore can deduce an accurate value of the τ^-

Table 5. Characteristics of the τ^- events.

Event no.	Kinetic energy of the primary MeV	Kinetic energy of the positive π-meson in the C.M.S. of the τ^- MeV	$\cos\theta$ (¹)
21	114	1.3	0.466
22	17	36.0	0.613
23	13	26.6 or 30.8	0.463 or 0.360

(¹) Defined in the text.

mass and our result is $m_{\tau^-} = 494.4 \pm 1.2$ MeV. The error was obtained from the spread in the Q-value from six independent measurements of the event and includes errors arising from the straggling of the pions, uncertainties in density, shrinkage factor and the pion mass. The mass of the π-meson $m_\pi = 139.63 \pm 0.06$ MeV was used [21].

In event 22 two π^- were stopped, the third pion left the stack. In event 23 one π^- was stopped and the other two pions left the stack. The tracks which left the stack were compatible with pions. It is possible even in the last case to calculate all desired momenta and energies from only the measured angles and the range of the stopped π. In all cases the kinematics fitted the τ^- decay.

It will be possible in the future, when the number of τ^- decays in flight increases, to investigate the spin of the τ^- in the same way as the spin of the τ^+ [22]. The energy distribution of the unlike pion and the distribution of $\cos\theta$, where θ is the angle at the instant of decay between the direction of the unlike pion and that of the two like pions in their own C.M.S., are sensitive to the spin character of the τ^-. For future reference we give the kinetic energy of the unlike pion in the τ^- frame of reference as well as the value of $\cos\theta$ in Table 5.

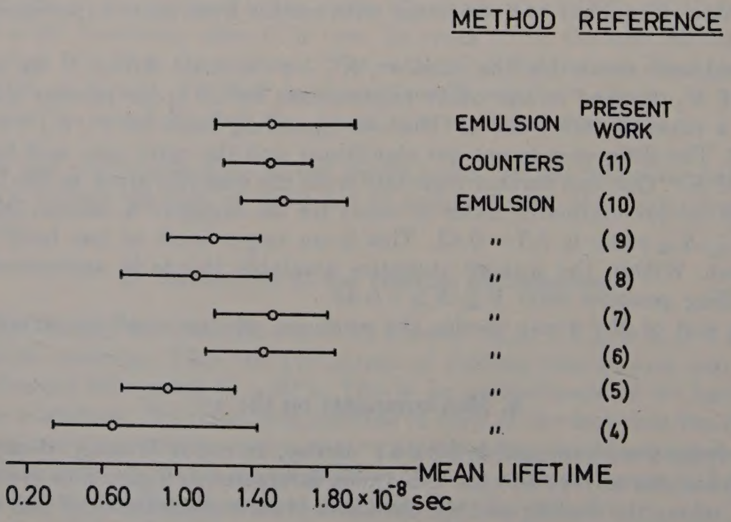

Fig. 2. Lifetime measurements for negative K-mesons.

7. Estimate of the lifetime

The total moderation time is 30.0×10^{-8} sec. in our experiment and the corrected total number of decays in flight 20 according to the foregoing discussion. We discard the information from the last 1 mm of stopping tracks and the top and bottom 30 μm of emulsion (unprocessed). The problem of getting an unbiased estimate of the mean life by means of the present method is fully discussed by B. Bhowmik *et al.* [2]. Finally 17 events are obtained in a moderation time of 25.2×10^{-8} sec.

Our estimate of the mean life is then

$$\tau_{K^-} = (1.50^{+0.45}_{-0.30}) \times 10^{-8} \text{ sec.}$$

The published values of the K^- mean lifetime are summarized in Fig. 2. There is an indication from the recent experiments that the lifetime might be larger than that of the K^+, although the evidences are not yet conclusive.

8. Conclusions

From the present experiment we can draw the following conclusions:

(i) Conclusive evidence exists for the τ^-, $K_{\mu 2}^-$ and $K_{\beta 3}^-$ modes of decay. We have further found events consistent with the $K_{\pi 2}^-$, $K_{\mu 3}^-$ and $K_{\pi 3}'^-$ modes of decay.

(ii) $K_{\mu 2}^-$ is the predominant decay mode of the negative K-mesons.

(iii) The ratio $\tau^-/K_L^- + \tau^-$ is $3/20 = 0.15$.

(iv) The ratio $K_{\pi 2}^-/K_{\mu 2}^-$ is $3/7 = 0.43$. This may be regarded as an upper limit, if there are nuclear reactions fitting the $K_{\pi 2}$ kinematics.

(v) The contamination of nuclear reactions for the events in flight with one charged light meson is $4/18 \sim 20\,\%$ in our experiment. This indicates that a careful investigation of the "decays in flight" is necessary in experiments on lifetimes and relative abundances.

(vi) The mean lifetime of the negative K-meson is $\tau_{K^-} = (1.50^{+0.45}_{-0.30}) \times 10^{-8}$ s.

(vii) From a τ^- decay in flight the mass of the negativ τ-meson was measured to be $m_{\tau^-} = 494.4 \pm 1.2$ MeV.

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